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ENERGY AND WATER BALANCE MODELING OF WINTER WHEAT

by

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Summary:

Water and energy balances of sprinkler irrigated winter wheat were measured at Bushland, TX over the 1989-90, 1991-92, and 1992-93 seasons. Water balances were measured using weighing lysimeters. Net radiation and soil heat flux were measured at each lysimeter and solar radiation, wind speed, air temperature and dew point temperature were measured at a nearby weather station over grass. The ENWATBAL model was used to predict evapotranspiration (ET), net radiation (R_n), and soil heat flux (G). These were compared to daily measured values with good results. Coefficients of determination (r²) ranged from 0.92 to 0.97 for linear regressions of estimated vs. measured ET; from 0.81 to 0.96 for R_n; and from 0.61 to 0.83 for G. The model underpredicted H and ET under windy conditions for a tall crop. Needed model improvements include a mechanism for including crop height in calculations of sensible and latent heat fluxes, and modifications for freezing conditions.

Keywords:

Energy Balance, Water Balance, Evaporation, Evapotranspiration, Lysimeters, Crop Modeling, Crop Water Use, Weather, Net Radiation, Soil Heat Flux, Sensible Heat Flux.

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Member Fellow Member

ABSTRACT

Methods of estimating evapotranspiration (ET) of winter wheat often use the concepts of reference evapotranspiration (ET_r) and a crop coefficient (K_c) which is multiplied by ET_r to give ET. The crop coefficient is usually related to number of days after planting (DAP) or to growing degree days (GDD). However, for three seasons of winter wheat grown on the Pullman clay loam at Bushland, Texas, curves of K_c vs. GDD or DAP were distinctly different. Alternatives to the K_c/ET_r concepts include modeling of the energy and water balances of the crop - soil system. We used the ENWATBAL mechanistic ET model to predict daily ET, net radiation (R_n) and soil heat flux (G) for the three seasons of wheat (1990, 1992, and 1993) and compared predicted values to those measured on weighing lysimeters. Since ENWATBAL uses leaf area index (LAI) as a data input we compared model results with measured values over the period from the first LAI measurement in the spring to the last measurement before harvest. Linear regressions of estimated ET vs. measured ET resulted in r^2 values of 0.94, 0.92, and 0.97 for the 1990, 1992 and 1993 years. Regression slopes ranged from 0.76 to 0.95 and intercepts ranged from 0.75 to 0.95 mm. Regressions of estimated vs. measured R_n gave r^2 values of 0.96, 0.81 and 0.89 for 1990, 92 and 93. Slopes ranged from 1.05 to 1.18 and intercepts ranged from -0.6 to -1.4 mm of water equivalent. Regressions of estimated vs. measured G resulted in r^2 values of 0.83, 0.61, and 0.82 for 1990, 92, and 93. Slopes ranged from 1.10 to 1.40 and intercepts ranged from -0.02 to -0.15 mm of water equivalent. Cumulative ET was overestimated by 11% and 4% in 1990 and 1993, respectively; and, was underestimated by 8% in 1992. Lodging of the tall 1992 crop probably caused worse predictions for that year. Mechanistic modeling was shown to be a feasible alternative to the K_c/ET_r method for estimating crop water use but requires additional data including LAI, half-hourly weather data and information on soil hydraulic characteristics and wheat rooting patterns.

Keywords: Energy Balance, Water Balance, Evaporation, Evapotranspiration,
Lysimeters, Crop Modeling, Crop Water Use, Weather, Net Radiation, Soil
Heat Flux, Sensible Heat Flux.

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INTRODUCTION

Winter wheat is a major crop in the Southern High Plains. Common methods of predicting wheat water needs use the concepts of potential or reference evapotranspiration (ET_r) and a crop coefficient that, when multiplied by ET_r, gives an estimate of evapotranspiration (ET). The crop coefficient or basal crop coefficient (K_{cb}) is considered to be related to number of days after planting or to growing degree days (GDD). However, use of these concepts can lead to difficulties. For example, curves of K_{cb} vs. GDD were distinctly different for each year for three seasons of wheat at Bushland, Texas, (Howell et al., 1993). The same was true if K_{cb} was plotted vs. time to heading or vs. days after planting. The differences may be attributable to different crop growth patterns over time, and to different weather patterns which affect net radiation. Better predictions may be available from models of crop water use that include crop growth and net radiation as inputs or that accurately predict crop growth and/or net radiation.

The ENWATBAL model (Evelt and Lascano, 1993) is a mechanistic ET model that computes the surface energy balances of the soil surface and crop canopy by finding the temperatures for these surfaces that solve their respective energy balance equations. The model uses leaf area index (LAI) and information about rooting depth as inputs. Other inputs needed are solar radiation (R_s), wind speed (U), air temperature (T), dew point temperature (T_{dew}), and the timing and amount of precipitation and irrigation. ENWATBAL has successfully estimated daily corn ET ($r^2 = 0.85$ to 0.96) and half-hourly mean net radiation (r^2 0.97) over a full season at the study site (Evelt et al., 1991). Daily bare soil evaporation was also well estimated by ENWATBAL in three experiments (r^2 of 0.84 , 0.94 and 0.99), as was half-hourly mean R_n (r^2 of 0.97 , 0.97 , and 0.97) (Evelt et al., 1992). The bare soil performance of a model is important since wheat LAI is typically low over the winter season. The purpose of this study was to find if ENWATBAL could accurately predict the energy and water balances of winter wheat over three seasons.

METHODS AND MATERIALS

Winter wheat was grown on the Pullman clay loam (fine, mixed, thermic Torrertic Paleustoll) over three seasons, 1989-90, 1991-92 and 1992-93, at Bushland, TX. Planting dates and crop phenology are given in Table 1. Wheat was grown on two, square, 4.4 ha fields each year, one of which was well-watered. Results from only the well-watered fields will be discussed. A 3-m by 3-m square by 2.4-m deep weighing lysimeter in the center of each field measured ET (Marek et al., 1988). Irrigations were applied with a lateral move sprinkler system equipped with spray heads at about 1.5 m above ground and 1.52 m apart. A nearby weather station over irrigated grass measured solar radiation, wind speed, air and dew point temperatures and barometric pressure (Dusek et al., 1987). Measurements were made every 6 s by a Campbell Scientific model CR7X data logger and half-hourly means were reported. At the lysimeters measurements of net radiation, wind speed, wet and dry bulb temperatures, transmitted solar radiation, soil temperature averaged over 0.02 to 0.04 m, and heat flux at 0.05 m depth were made every 6 s using a CR7X data logger, while the lysimeter load cell was measured every 2 s, and half-hourly means were reported. Soil water content was measured from 0.1 to 1.9 m depths at 0.2 m increments, using a

Campbell Nuclear Pacific, Inc.³ model 503DR neutron scattering moisture gage, in two galvanized steel access tubes in each lysimeter and four access tubes in the field adjacent to each lysimeter. The gage was previously field calibrated for the A, B and calcic B horizons with r^2 values of 0.90, 0.96, and 0.97, respectively. Leaf area index was measured from whole plant samples (3 replicates each of 1 m row length) taken periodically throughout the season. Root growth was measured in 1993 on a nearby well-watered wheat field by washing 0.05 m diameter soil cores, counting the roots against a 0.01 cm grid and converting the counts to root length density using Tennant's (1975) method (J.T. Musick, personal communication). The cores were sectioned into 0.05 m deep samples from 0 to 0.3 m soil depth, and into 0.1 m samples below 0.3 m soil depth. Three replicates were taken.

The ENWATBAL model was initialized with the average soil water contents and temperatures measured in the lysimeters on the model start day (Table 1). Relationships of soil water content vs. soil water potential and soil hydraulic conductivity vs. soil water content were those used by Steiner et al. (1989). The relationship between soil albedo and soil surface water content (water content in the top 0.008 m of soil) was developed from measurements of albedo of Pullman soil that was freshly irrigated and air dry, respectively. Albedo was described in the model as being 0.11 from water contents of 0.49 (saturated) to 0.25 $\text{m}^3 \text{m}^{-3}$, and varying linearly with water content from 0.11 to 0.20 as water content declined from 0.25 to 0 $\text{m}^3 \text{m}^{-3}$. Soil thermal conductivity, λ ($\text{J s}^{-1} \text{m}^{-1} \text{K}^{-1}$), was a function of soil water content, θ ($\text{m}^3 \text{m}^{-3}$):

$$\lambda = -0.07 + 3.31(\theta) \quad [1]$$

as measured by Evett (1994). Micrometeorological input data were the half-hourly solar radiation, wind speed, and air and dew point temperatures from the grass weather station. Precipitation input data were developed from the weather station input data and recorded depths and times of irrigation. Curves of LAI were developed from the field LAI measurements using a combination of piecewise linear and cubic spline fitting and daily LAI values were calculated from the curve for each year (Fig. 1).

Rooting depth was assumed to increase linearly with time from the depth of planting on the day of planting to 1.2 m on day 55 of the next year (first day for which measurements were available). The depth of maximum root length density RLD was constant at 0.1 m for all measurements and was assumed to be 0.1 m for all days. The rooting function in ENWATBAL was modified to accommodate the non-triangular rooting pattern of wheat by including a second inflection point (Fig. 2). The depth of maximum RLD, RM (m), was the first inflection and was constant at 0.1 m over the season. The depth of the second inflection, RI (m), varied between 0.20- and 0.25-m over the season.

³The mention of trade or manufacturer names is made for information only and does not imply an endorsement, recommendation, or exclusion by USDA-Agricultural Research Service.

The rooting function, RF (dimensionless), for a particular depth, D (m), was calculated as:

$$\begin{aligned}
 \text{RF} &= D / \text{RM}, & \text{Depth} &\leq \text{RM} \\
 \text{RF} &= 1 + (1 - \text{RIFRAC})(\text{RM} - D)/(\text{RI} - \text{RM}), & \text{RM} &< \text{Depth} < \text{RI} \\
 \text{RF} &= \text{RIFRAC} + \text{RIFRAC}(\text{RI} - D)/(\text{RD} - \text{RI}), & \text{RI} &\leq \text{Depth} \leq \text{RD} \\
 \text{RF} &= 0, & \text{Depth} &> \text{RD} \quad [2]
 \end{aligned}$$

where RD is the maximum depth of effective roots in m, and RIFRAC is the fraction of maximum RLD existing at the depth of the second inflection. The rooting function values calculated for each soil layer (or finite difference grid point) with Eq. 2 were then normalized so that the total rooting function for all layers was unity.

RESULTS AND DISCUSSION

Because the ENWATBAL model relies on accurate input data for daily LAI we compared model outputs with measured data only until the day of the last LAI measurement for each year. Also, the lysimeter measured ET values are relatively inaccurate on irrigation days since there is no reliable check on the depth of irrigation received by a particular lysimeter. Thus, we omitted irrigation days from analysis of ET results. Estimated ET was well and linearly correlated with measured ET for each year although relationships deviated from one to one correspondance (Table 2, Fig. 3). Intercepts were positive and slopes were less than unity for all years. The model tended to overpredict ET on days with low ET for 1990 and 1993. In 1993 ET was somewhat underpredicted on days with high ET. Underprediction on days with high ET was worse in 1992 when the wheat lodged severely. Cumulative ET was overpredicted by 4% in 1993 and 11% in 1990; and, was underpredicted by 8% in 1992. In the model the resistances to sensible and latent heat flux, and the transmission factor for radiation are computed on the basis of LAI. These relationships were developed for an assumed spherical canopy geometry by Lascano et al. (1987) using a multi-layer canopy model. Also, the relationship between stomatal conductance and solar radiation used by the model is for sorghum. Development of new relationships based on wheat canopy geometry may improve the ET estimates.

Net radiation was less well modeled with linear regressions of estimated vs. measured values resulting in r^2 values of 0.81, 0.89 and 0.96 for 1990, 92 and 93, respectively (Table 2). Slopes were greater than unity and intercepts were slightly negative (Fig. 4). There were 8 days with snow cover early in 1992 and these were omitted from the regression analysis, but Fig. 4 shows that R_n was overestimated by the model on days with snow which are represented by a cluster of points at the left side of the graph. Soil heat flux was well estimated in 1990 and 1993 with slopes of 1.15 and 1.10 and small intercepts for regression of estimated vs. measured G (Table 2, Fig. 5). This is an improvement of previous model results for corn when G was overestimated by as much as 100% (Evet et al., 1990) and tends to verify the relationship between thermal conductivity and soil water content developed by Evett (1994). Wheat lodging in 1992 reduced the transmitted

radiation and reduced the measured soil heat flux. The model did not reflect this, resulting in a slope of 1.40 for regression of estimated vs. measured G and an r^2 value of 0.61.

Illustrative comparisons of the measured and modeled energy balance components were made for two consecutive days in 1992. The first day, day 119 (April 28), was windy (mean 2 m wind speed, U_2 , of 5 m s^{-1}) and the second day, day 120, was more normal for Bushland ($U_2 = 2.3 \text{ m s}^{-1}$). Solar radiation totaled 26.1 and 26.7 MJ m^{-2} for days 119 and 120, respectively. Dew point temperatures at 2-m elevation averaged about the same at 4.1 and 4.7 °C while 2-m air temperatures averaged 20.1 and 18.3 °C for days 119 and 120. Profile soil water content was above 85% of field capacity and LAI was 7 so canopy cover was complete. Sensible heat flux for the lysimeters was calculated as the residual of measured energy balance components as:

$$H = -R_n - ET - G \quad [3]$$

Values were converted to mm of water equivalent for ease of comparison. For day 119 the model underestimated ET by 23% (Fig. 6) although R_n and G were very well estimated. The discrepancy in the energy balance was due to underprediction of sensible heat flux by the model under the windy conditions (Fig. 6, bottom). Net radiation was again very well predicted for day 120 (Fig. 7, middle). Soil heat flux was overpredicted during midday and sensible heat flux predictions, while fairly close to measured, were underpredicted in the afternoon (Fig. 7, bottom). The result was underprediction of ET by 13% for day 120 (Fig. 7). Underprediction of sensible heat flux is probably tied to the fact that the 1992 crop was much taller than those of 1990 and 1993. The taller crop would have reduced aerodynamic resistance and the resulting increased sensible heat flux would provide the energy for increased ET. This would explain the overall underestimation of ET for 1992. In general this suggests that LAI alone is insufficient to predict resistances to sensible and latent heat fluxes when crop height is highly variable between cultivars.

SUMMARY

The ENWATBAL model provided generally good to excellent predictions of energy and water balance components for three seasons of winter wheat and over a range of LAI from 0.5 to 7.0. Model predictions of net radiation and sensible heat flux could probably be improved by generating new relationships between LAI and canopy transmission coefficients for short and long wave radiation, and between LAI and canopy resistance to sensible and latent heat flux. However, the results for 1992 showed that LAI alone may not be sufficient for good prediction and the model may need to include some crop height information as a data input. The good correspondance between measured and estimated soil heat flux indicates that the thermal conductivity vs. soil water content relationship is appropriate for the Pullman clay loam soil. In order to model the complete wheat season, further work is needed to enable the model to operate when temperatures are at or below zero, including soil freezing/thawing, snow accumulation and melting, and albedo changes.

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Table 1. Agronomy and phenology.			
Season	1989-90	1991-92	1992-93
Well-Watered Field	NW	NE	SW
Cultivar	TAM 200	TAM 107	MESA (Agripro)
Plant density (No. m ⁻²)	190	193	131
Planting (year, day)	89, 283	91, 270	92, 273
Emergence	89, 291	91, 280	92, 283
Heading	90, 129	92, 118	93, 125
Anthesis	90, 136	92, 129	93, 133
Maturity	90, 165	92, 171	93, 172
Harvest	90, 177	92, 188	93, 179
Model begin	90, 61 LAI 0.53	92, 63 LAI 2.04	93, 57 LAI 0.71
Model end	90, 158 LAI 1.35	92, 140 LAI 3.57	93, 140 LAI 3.72

Table 2. Linear regressions for estimated ET, Rn and G against measured values.			
<u>Year</u>	<u>Regression Equation</u>	<u>r²</u>	<u>N</u>
<u>Evapotranspiration</u>			
1989	Est. ET = 0.75 + 0.948(ET)	0.94	84
1992	Est. ET = 0.95 + 0.763(ET)	0.92	68
1993	Est. ET = 0.91 + 0.866(ET)	0.97	73
<u>Net Radiation</u>			
1989	Est. Rn = -1.40 + 1.182(Rn)	0.96	98
1992	Est. Rn = -0.60 + 1.046(Rn)	0.81	68
1993	Est. Rn = -1.24 + 1.168(Rn)	0.89	82
<u>Soil Heat Flux</u>			
1989	Est. G = -0.02 + 1.096(G)	0.83	95
1992	Est. G = -0.15 + 1.396(G)	0.61	77
1993	Est. G = -0.08 + 1.149(G)	0.82	81

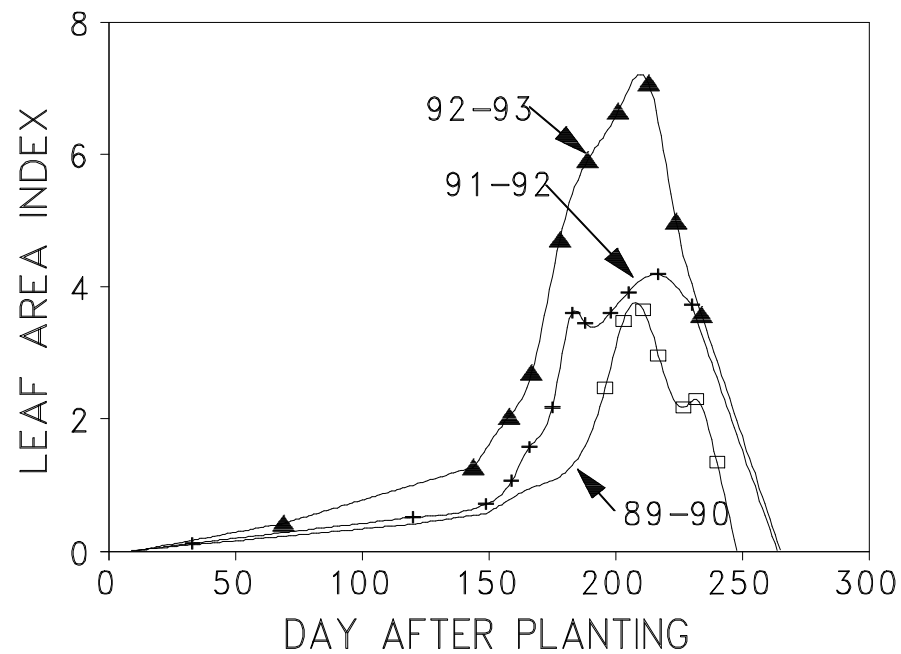


Figure 1. Leaf Area Index for three wheat seasons.

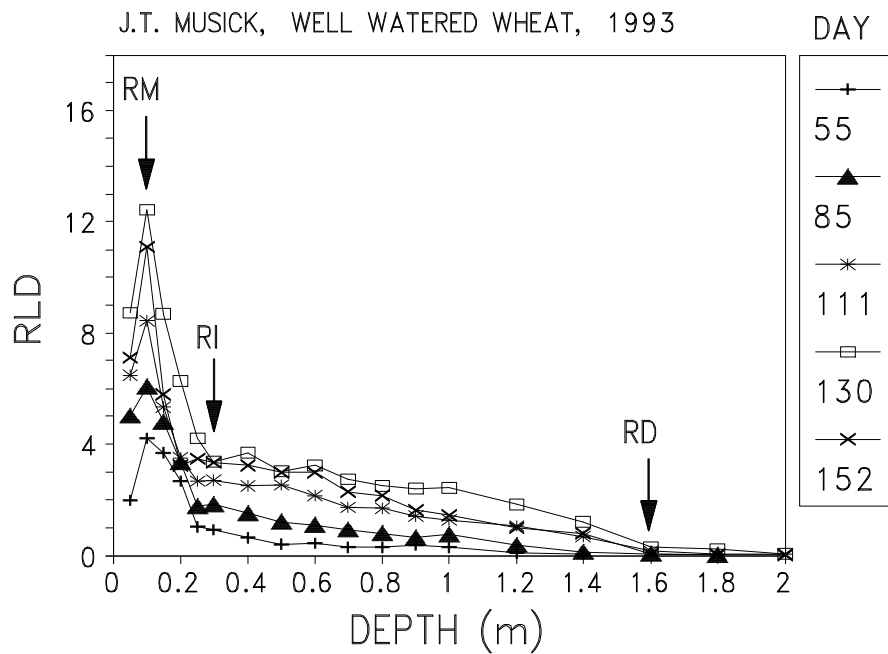


Figure 2. Typical wheat rooting patterns and illustration of depths RM, RI, and RD in Eq. 2.

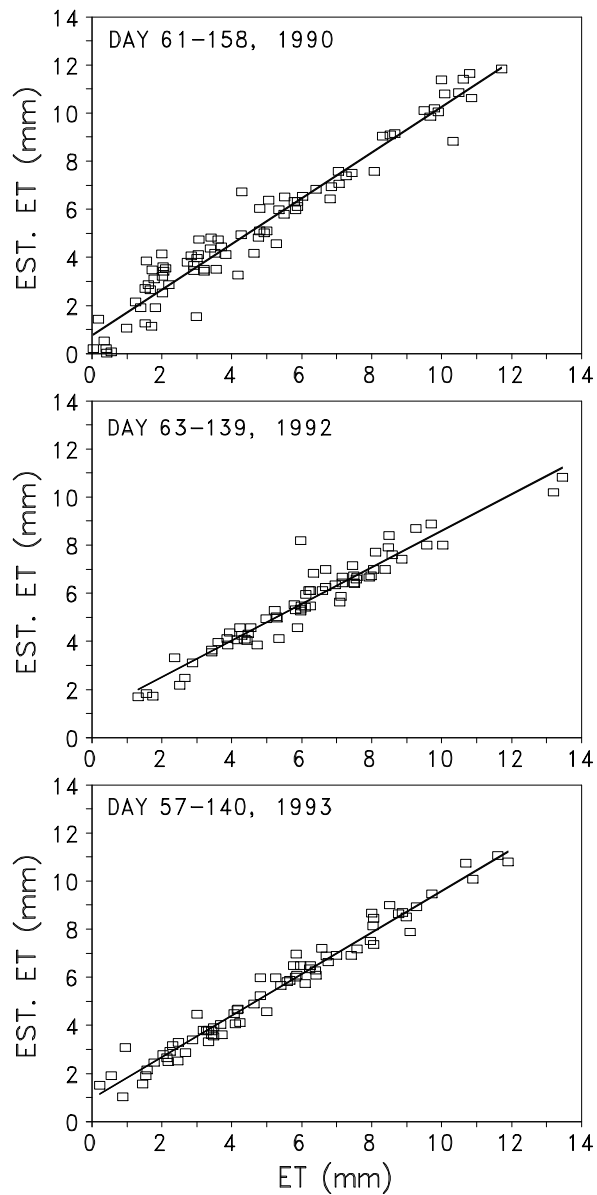


Figure 3. Daily estimated vs. measured ET for 3 wheat seasons, irrigation days omitted. Lines are regression lines.

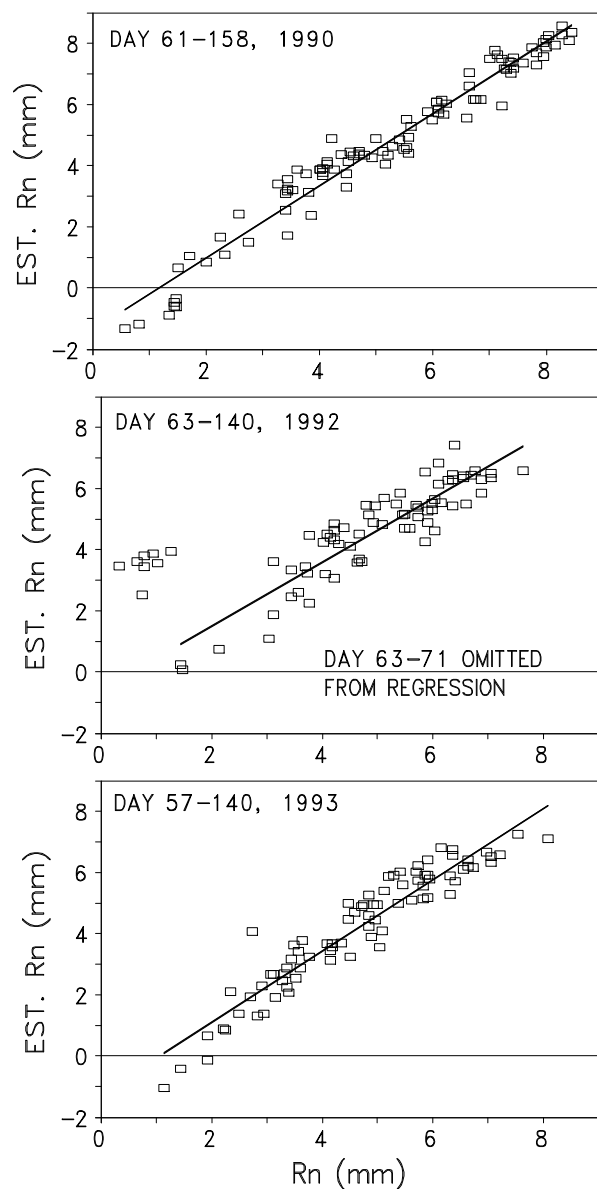


Figure 4. Daily estimated vs. measured Rn for 3 wheat seasons, snow days omitted. Lines are regression lines.

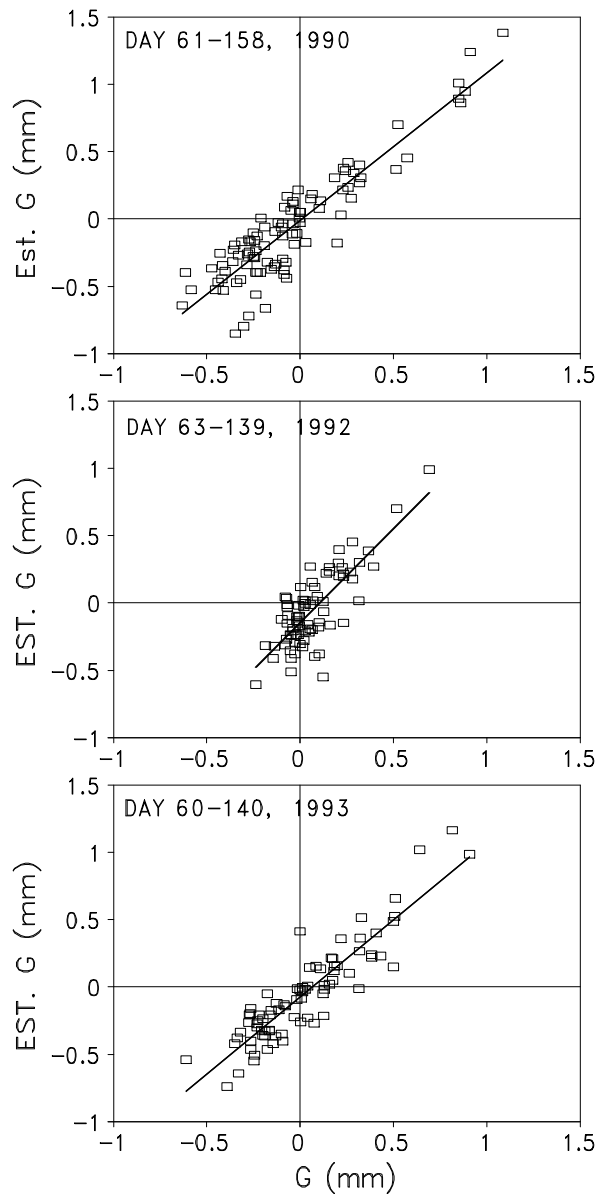


Figure 5. Daily estimated vs. measured G for 3 wheat seasons. Lines are regression lines.

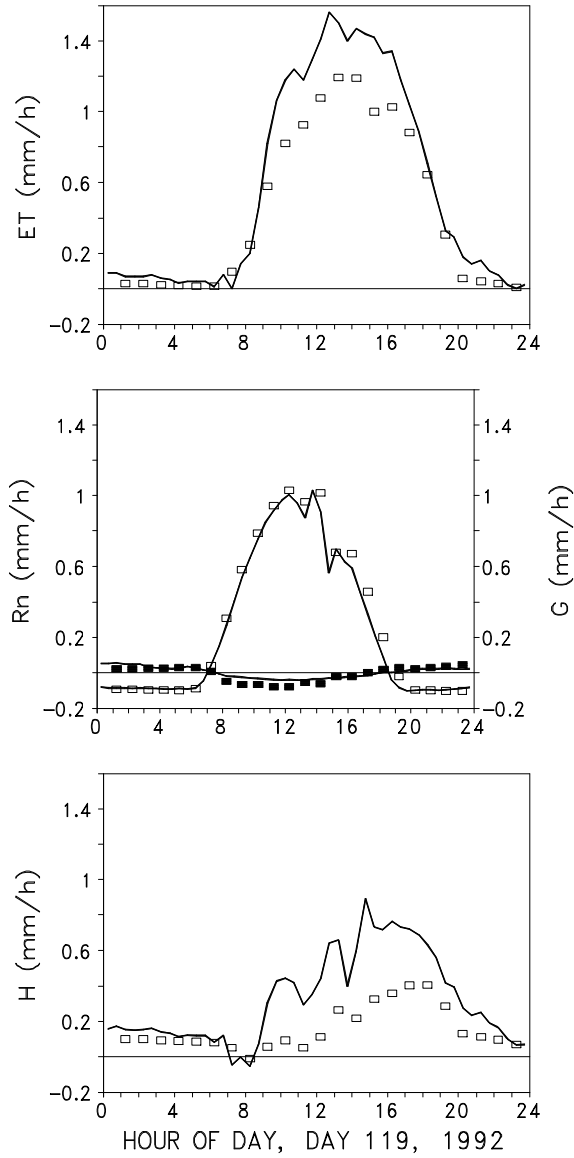


Figure 6. Measured and estimated energy balance components for day 119, 1992. Lines are measured values, boxes are model results. For the middle graph the open boxes are Rn, black boxes are G; the solid line is Rn and the dotted line is G.

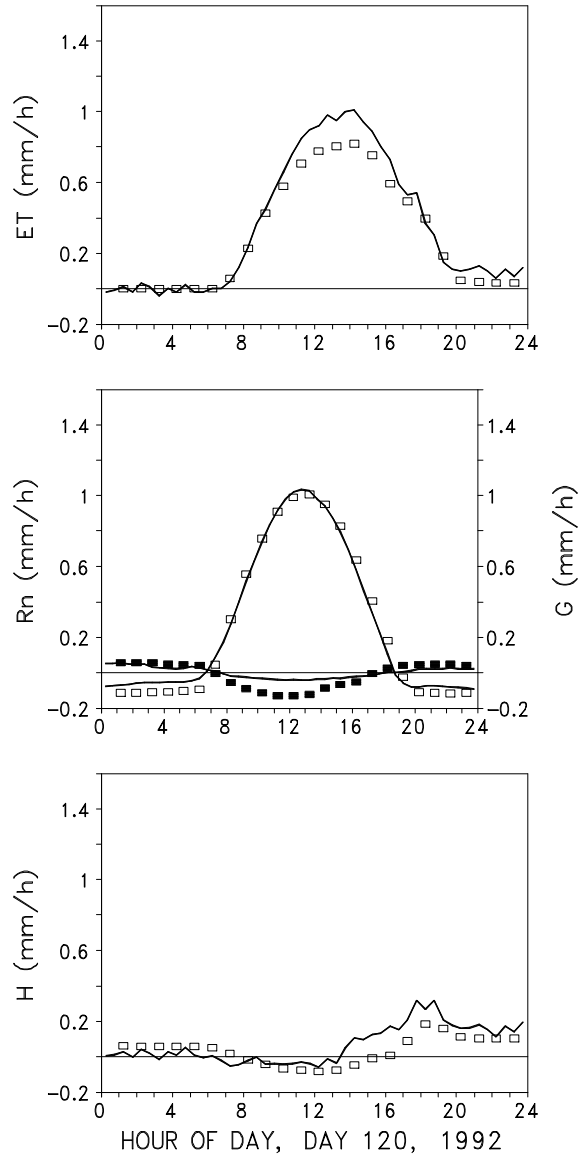


Figure 7. Measured and estimated energy balance components for day 120, 1992. Lines are measured values, boxes are model results. For the middle graph the open boxes are Rn, black boxes are G; the solid line is Rn and the dotted line is G.